# FIELD HYDROLOGICAL TESTS OF EXPLOSIVELY FRACTURED COAL*

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## INTRODUCTION

Hydrologic tests were made in the explosively fractured Felix No. 2 coal seam on part of the Lawrence Livermore Laboratory in-situ coal gasification experiment at the Hoe Creek site 24 km SW of Gillette, Wy. (1) The purposes were to evaluate wells and regions to be gasified and to gain information for improvement of explosive effects predictions.

In this paper related prior work is summarized and preliminary interpretations of the post-fracturing hydrological tests are given.

## REVIEW OF PRIOR FIELD WORK

### Hydrogeology (2,3)

The subbituminous Felix coal occurs within the Eocene Wasatch Formation and at the experimental site consists of two nearly horizontal seams, Felix No. 1 and Felix No. 2 in descending order. They are of nearly constant thickness, 3 m and 7.6 m respectively, and separated by approximately 5 m of siltstone-claystone unit. The Felix No. 2 is underlain by at least 3 m of a claystone-shale unit. A typical lithologic sequence of near-surface strata is shown in Fig. 1.

The water table is approximately 23 m above the top of the Felix No. 2 coal which can be characterized as a leaky anisotropic aquifer. Its average horizontal fracture permeability is 0.3 darcy. Its axis of maximum permeability (0.4 darcy) trends N59°E corresponding approximately to the average bearing, N70°E, of the most prominent set of vertical fractures (face cleat). Table 1 lists these and other results for the coal and associated strata. Surface locations of test wells are shown in Fig. 2.

### Explosive Fracturing and Permeability (4)

Two charges, each of 340 kg of explosive, were fired simultaneously on Nov. 5, 1975, in the bottom 1.5 m of the coal (Wells HE and INJ,** Fig. 3). The horizontal separation was 7 m.

At this time, predicted pattern of permeability enhancement in the horizontal plane of the charges showed a joined region of 100 darcies or greater at the charge locations and a decrease of permeability with distance out to the native coal (0.3 darcy) at approximately 13 m. Other possible effects combinations were recognized including compaction at a distance around each charge and decreases in permeability due to generation of finely sized particles.

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**Later redesignated I-O.

Table 1. Hydraulic characteristics of Felix coal and associated strata, Hoe Creek site, pre-shot.[a]

| Stratum | Horizontal permeability darcy | Coefficient of storage | Vertical permeability darcy |
|---|---|---|---|
| Felix No. 1 | 0.47 to[b] 1.42[c] | $2 \times 10^{-2}$ | — |
| Strata between Felix No. 1 and No. 2 | 0.12[c] | $2.24 \times 10^{-3}$[d] | 0.022[d] |
| Felix No. 2 | 0.41[e]<br>0.23[f] | $1.18 \times 10^{-3}$ | — |
| Strata below Felix No. 2 | — | — | <0.0015[g] |

[a]Dashes indicate that no measurement was made.

[b]A range of values is given for two different-type single-well tests in the same well.

[c]Results from slug-injection tests.

[d]Values are averages for the total thickness of strata between Felix No. 1 and Felix No. 2 coals.

[e]Value along the axis of maximum hydraulic conductivity, which trends N 59° E.

[f]Value along the axis of minimum hydraulic conductivity, which trends N 31° W.

[g]Refers to average values for first 2.1 m of strata below bottom of Felix No. 2 coal.

## Initial Post Fracturing Hydrologic Tests (4,8)

We tried pulse tests and sustained constant-rate pumping (drawdown) tests to measure permeability in the heterogeneous explosive-fractured region. Both showed average enhanced permeabilities of 2-4 darcy for assumed radially symmetric regions. Definition was limited by number of observation wells and locations. Analysis of pumping tests was by drawdown difference between wells after the rate of change had slowed (quasi-steady-state). A repeated pumping test gave higher results but within a factor of 2 for most observation wells. Results are shown in Table 2.

Observation of unchanging hydraulic head in the Felix No. 1 coal (Well 12-OW) during testing indicated that there had been no major change in vertical leakage into the Felix No. 2 coal attributable to the explosive fracturing.

These results along with air-flow tests and new computer calculations of fracturing were the base for field modifications for a gasification test.

Table 2. Results of initial post-fracturing permeability tests. Analysis was by drawdown difference at a fixed late time except as noted.

| Pumped well | Observed well | Permeability darcy |
|---|---|---|
| 9-OW | 3-OW | 3.0 |
| | 8-OW | 2.2 |
| 9-OW (2 min pulse) | 3-OW | 2.3 |
| | 8-OW | 2.3 |
| INJ (NOV) | I-1 | 1.5 |
| | 3-OW | 1.7 |
| | 9-OW | 3.3 |
| | HE | 1.6 |
| | 8-OW | 1.7 |
| | 4-PW | 0.7 |
| INJ (DEC) | I-2 | 3.3 |
| | 3-OW | 4.2 |
| | HE | 2.7 |
| | 8-OW | 3.4 |

## Modified Well Pattern, Completions and Instruments (5,6,7)

In preparation for gasification along the INJ-HE axis, a pattern of dewatering wells, production well* and instrument wells was provided. Figure 4 shows the locations as completed. Figure 5 shows the surface locations of 5 environmental monitoring wells placed at 2 distances, approximately 15 m and 30 m out. Well completions were such that the injection and dewatering wells could be approximated as fully penetrating the Felix No. 2 coal and well P-1 as partially penetrating, open in the bottom 1.5 m of the coal. Typical wells are shown in Fig. 6. The dewatering, production and environmental wells were cleaned and developed by methods similar to those used for the pre-shot hydrology wells. (2) Bubbler tubes ended near the base of the coal. Bubblers were equipped with metered nitrogen gas supplies and pressure transducers for hydraulic head measurement and transmission. All available wells and instrument holes were provided bubblers with the exception of the five environmental wells in which we used well sounders manually. Pumps, piping and instruments were arranged to provide for hydraulic testing as well as gasification use. Data recording equipment consisted of strip chart recorders and a data acquisition computer with magnetic and printed paper-tape outputs, all in parallel.

## Post Explosion Core Sampling (7)

In order to obtain more information on fracturing, four cores had been taken completely through the Felix No. 2 coal seam at locations 1.8 m to 2.7 m from shot sites. All were found to be similar in appearance, with moderate to heavy fracturing in the top of the coal, followed by a less fractured zone, and then by a heavily

*Designated PROD-1 initially and changed to P-1 later.

fractured zone in the bottom 1.5 m to 3 m. The core between the explosives locations showed the most fracturing, the core farthest away from either exhibited the least fracturing.

## PRE-GASIFICATION HYDROLOGICAL TESTS (7)

### Summary of Results and Discussion

During development we found an unacceptably low water flow rate into well P-1, 0.006 ℓ/sec (0.1 gpm). We reviewed possible causes and made contingency plans for remedial work on P-1 and drilling of a diagnostic and potential replacement well, P-2. We suspected cement intrusion or completion in a low permeability region.

Consideration of the fracturing pattern as shown by the core samples and of flow behavior in upper and lower portions of the Felix No. 2 coal during drilling and earlier well tests before and after explosive fracturing led to the interpretation that although flows in the native coal were reasonably homogeneous vertically, post-explosion flow conditions were not uniform. While cracks created by the explosion may promote high flows in the upper regions, fines generated by the explosions tend to restrict or plug flow in the lower regions.

We enlarged P-1 to 1 m diameter in the bottom 1.5 m of coal and found that it produced 0.06 ℓ/sec (1 gpm), still less than desired. This work required removal of the screen and sump liner. We next drilled well P-2 in three stages of depth in the Felix No. 2 coal for flow measurements. The top half produced 0.4 ℓ/sec (7 gpm); the next quarter produced 0.02 ℓ/sec (0.3 gpm), the bottom half 0.03 ℓ/sec. This indicated lower permeability in the bottom part of the coal at least in the vicinity.

We then reinstalled the sump liner in P-1. While washing the liner in place a path opened hydraulically. Test flow was 0.63 ℓ/sec (10 gpm). A short pumping test of P-1 drew the water levels in I-5 and P-1 well into the coal, indicating a channel in the lower half of the coal (Fig. 7) across the shot region at HE. We could proceed with hydrological tests of the overall region and wells.

The specific capacity of the dewatering wells ranged from 0.7 to 7 gpm per ft of drawdown. Wells DW-1 and DW-6 showed the highest capacities. Results are in Table 3.

Graphical interpretations of drawdown tests by pumping I-0 and P-1 at constant rates show two regions of enhanced permeability, one about each of the explosion centers out to 3 m and a region of intermediate enhancement on out to the native coal at 15 m. The permeabilities obtained are: 14 darcy and 7 darcy respectively for regions at I-0 and P-1; and 1.5 darcy for the intermediate region. Figures 8 and 9 show these graphs.

Table 3. Relative performance of dewatering wells.

| Well No. | Specific capacity (gpm/ft) |
|---|---|
| DW-1 | 0.71 |
| DW-2 | 0.15 |
| DW-3 | 0.07 |
| DW-4 | 0.19 |
| DW-5 | 0.07 |
| DW-6 | 0.59 |

The apparent discontinuity shown in Fig. 9, for the data within 10 ft, may be due to the channel opened in final work on P-1 and to its non-symmetrical location.

The same method of analysis of drawdown tests of dewatering wells gave lower results for the inner (core) regions and higher values for the intermediate region. This is apparently a result of nonuniformity of flow field about the dewatering wells.

Late time drawdown data indicated some vertical leakage from the unit above the coal but again, approximately the same as pre-shot. Estimated vertical permeability values of 3 to 5 md were obtained.

Short, simultaneous injection-withdrawal tests (2-well recirculation) were made to investigate the permeability in the I-0 and HE regions. These tests were analyzed utilizing flow net techniques. Drawdown equipotentials were plotted on a plan view and selected flow lines drawn perpendicular to the equipotentials. Permeabilities of different areas were calculated by the gradient method wherein the gradient was obtained from the equipotential surface and the flow was apportioned via the flow net construction. An areal or field permeability K is calculated from the equation $K = Q/iA$, where Q is the flow in a region, i is the hydraulic gradient in that region, and A is the vertical section of the region through which the flow passes. Figures 10 and 11 are flow nets drawn for pumping P-1 to I-0 and DW-4 to DW-6.

Figure 12 is a composite prepared from results of flow net analyses and drawdown tests. The estimates of permeability for the inner core regions, 10 d at HE and 20 d at I-0, and the near native zone, 0.5 d, between the explosion centers are from the flow nets. The flow net and drawdown results for the inner enhanced permeability regions are consistent. The dashed lines on Fig. 12 connect well pairs in which the closeness of movement of water level during drawdown testing indicate a fracture or flow channel between them. The P-1 to I-0 test does not show the low permeability zone between explosion centers seen in the DW-4 to DW-6 test because of the symmetrical placement of the zone with respect to pumping from P-1 to I-0.

Analysis of the hydraulic response of the explosive-fractured coal is complicated by the strong radial variation of permeability and the presence of many relatively large sized well casings. In addition some of the fractures have become conduit-like in their ability to equalize pressure between certain observation well pairs or cause an uneven distribution of flow when one of the pair is a pumped well.

Figure 13 shows an outline of the gasification path indicated by thermocouple data on a simplified version of the composite sketch. The composite suggests a more westerly veering path to avoid the intermediate near native zone of coal.

Further evaluation and interpretation of the hydrological data are needed and a comparison with post burn core sample results when available.

The critical importance of permeabilities and their distribution is that the in-situ flow paths and thus the reaction zone configuration are determined by them. A given permeability net tends to determine ultimate resource recovery efficiency. In view of the importance of the deduced permeability net, it is important to further develop field tests and analysis techniques. Simple methods for measurement of the absolute or relative local permeabilities at several depths through a fractured seam are needed.

## REFERENCES


(1) Charles B. Thorsness, Richard W. Hill, and Douglas R. Stephens, "Preliminary Results from an In-Situ Coal Gasification Experiment Using Explosive Fracturing," Preprint, Joint ACS-CIC Conf., Montreal, Canada, May 29, 1977.

(2) Randolph Stone and David F. Snoeberger, "Evaluation of the Native Hydraulic Characteristics of the Felix Coal (Eocene, Wasatch Formation) and Associated Strata, Hoe Creek Site, Campbell County, Wyoming," Lawrence Livermore Laboratory, Rept. UCRL-51992, Jan. 8, 1976.

(3) Randolph Stone and David F. Snoeberger, "Cleat Orientation and Areal Hydraulic Anisotropy of a Wyoming Coal Aquifer," Lawrence Livermore Laboratory, Rept. in preparation.

(4) LLL In-Situ Coal Gasification Program Quarterly Progress Report, October through December, 1975, Lawrence Livermore Laboratory, Rept. UCRL-50026-75-4 (1976).

(5) LLL In-Situ Coal Gasification Program Quarterly Progress Report, January through March, 1976, Lawrence Livermore Laboratory, Rept. UCRL-50026-76-1 (1976).

(6) LLL In-Situ Coal Gasification Program Quarterly Progress Report, April through June, 1976, Lawrence Livermore Laboratory, Rept. UCRL-50026-76-2 (1976).

(7) LLL In-Situ Coal Gasification Program Quarterly Progress Report, July through September, 1976, Lawrence Livermore Laboratory, Rept. UCRL-50026-76-3 (1976).

(8) Albert E. Sherwood, R. Quong, and D. F. Snoeberger, "Permeability of Explosive Fractured Coal — Aquifer Modeling and Analysis of Field Hydraulic Data," Lawrence Livermore Laboratory, Rept. in preparation.

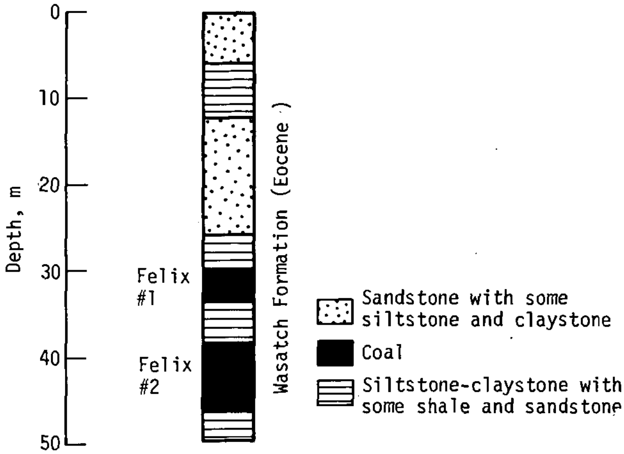


Fig. 1 Typical sequence of near-surface strata of the Hoe Creek site.

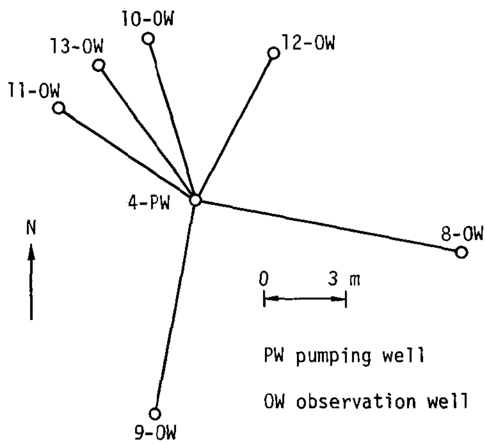


Fig. 2. Surface locations of test wells

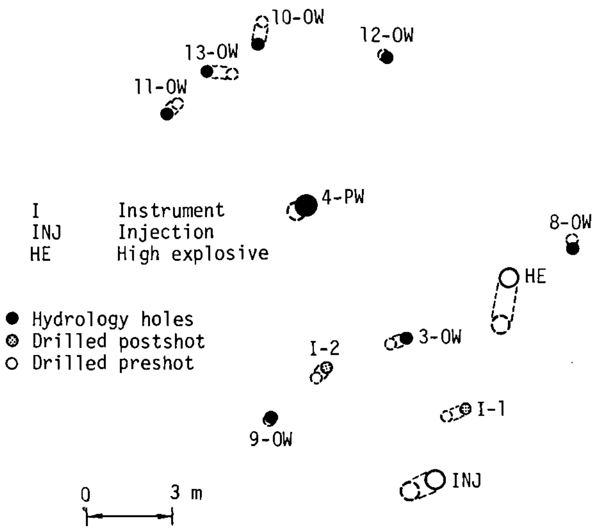


Fig. 3. Hole locations related to explosive fracturing. Dashed circles indicate positions of hole bottoms.

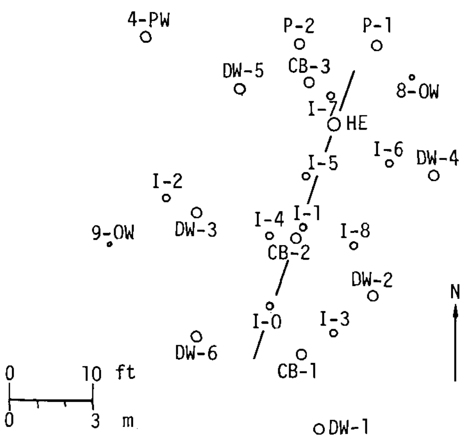


Fig. 4. Locations of wells and core holes (I-8, CB-1, -2, -3).

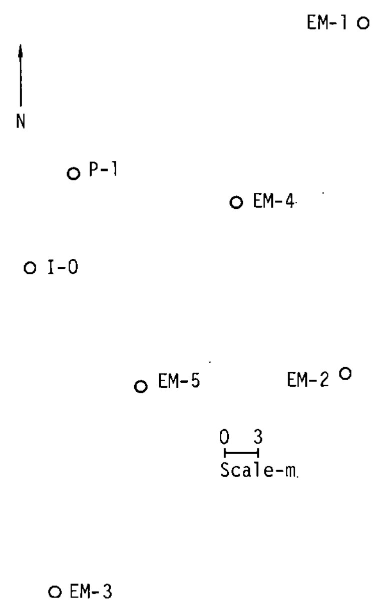


Fig. 5. Surface locations of environmental monitoring (EM) wells, 15 m and 30 m out from I-0 and P-1.

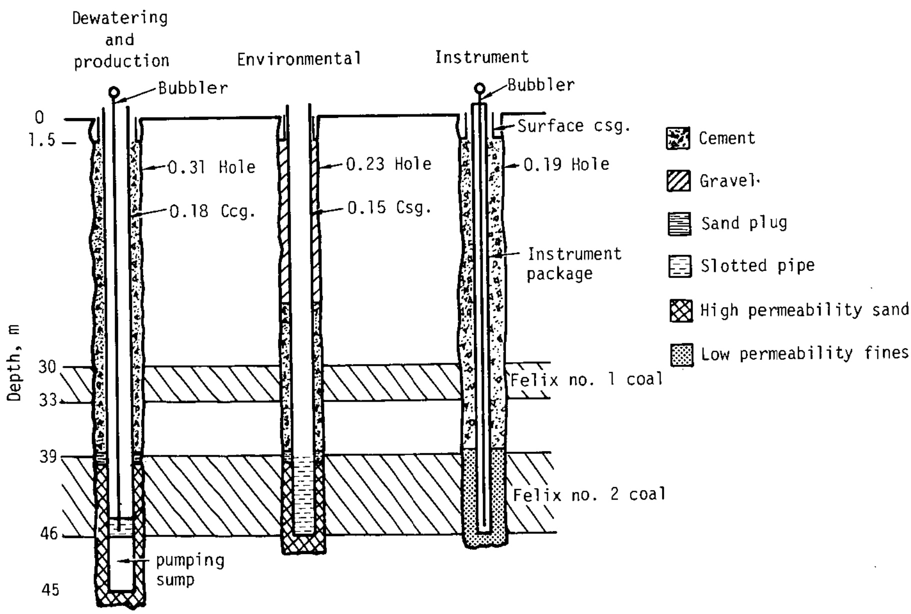


Fig. 6. Typical well and instrument completions. Dimensions are in meters.

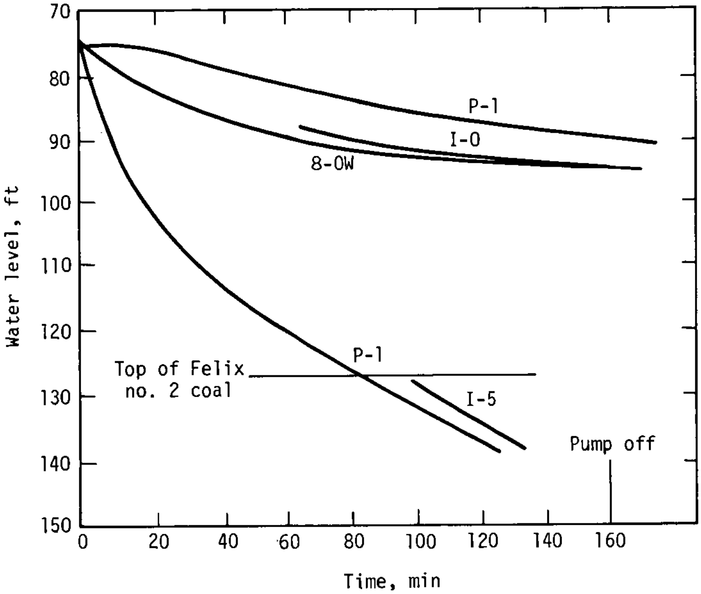


Fig. 7. Water level drawdowns by pumping well P-1 at 0.63 ℓ/sec (10 gpm).

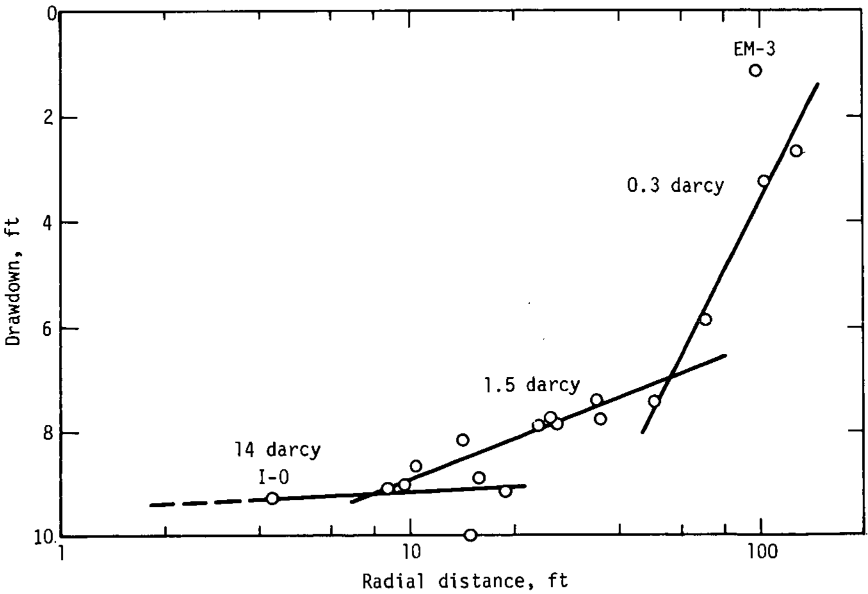


Fig. 8. Drawdowns, by pumping I-0 at 3 gpm, versus radial distance from I-0.

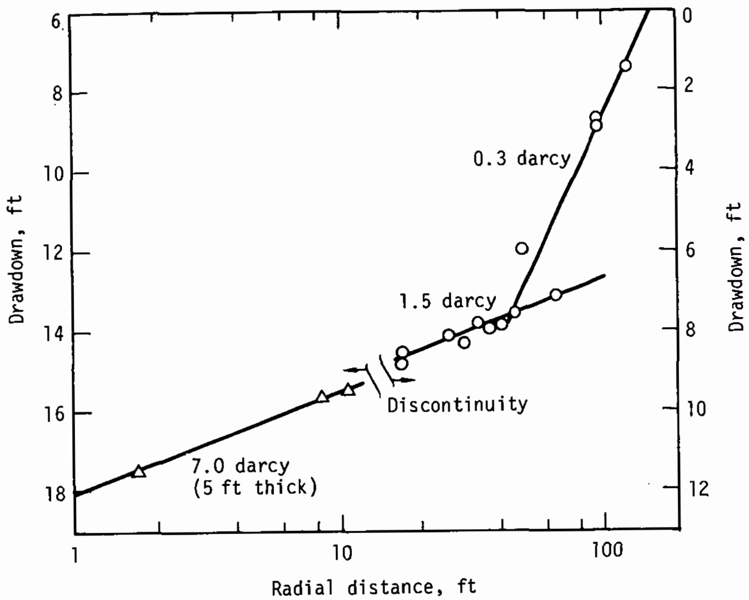


Fig. 9. Drawdowns, by pumping P-1 at 3.2 gpm, versus radial distance from P-1.

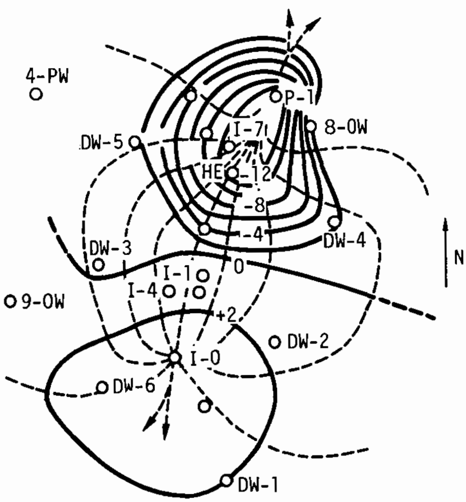


Fig. 10. Flow net. Hydraulic head (potential) contours and flow lines indicated by pumping 15 gpm from P-1 into I-0.

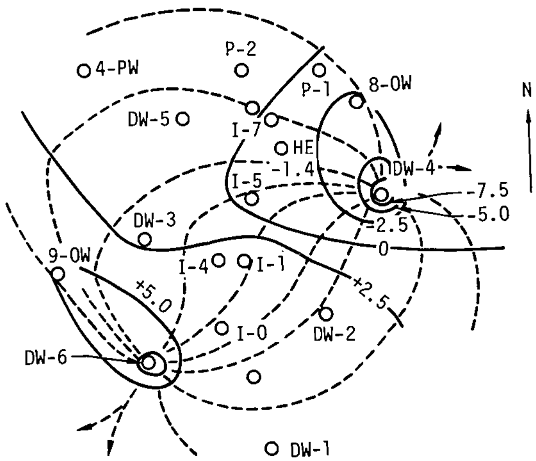


Fig. 11. Flow net. Hydraulic head (potential) contours and flow lines indicated by pumping 7.2 gpm from DW-4 into DW-6.

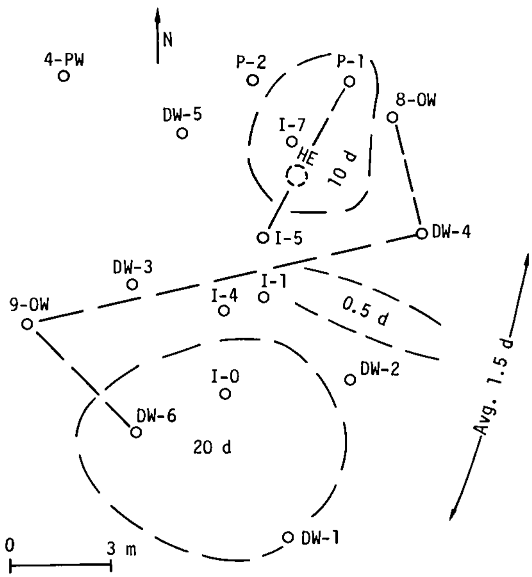


Fig. 12. Heuristic composite of channels or fractures (dashed lines), inner enhanced regions and near native zone between the explosion centers.

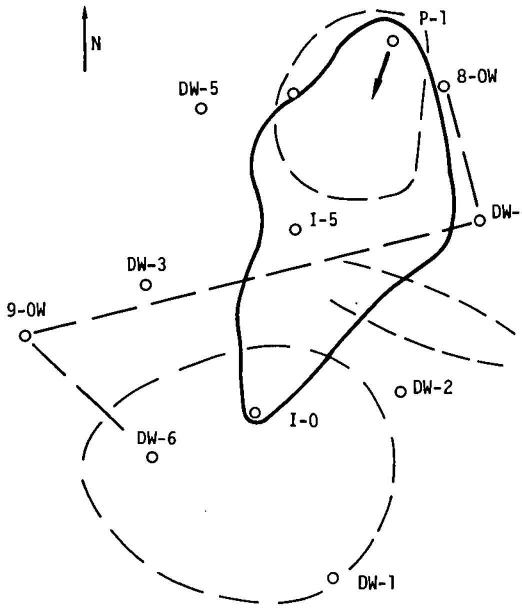


Fig. 13. Gasified region overlain on hydrology composite. Burn progressed from P-1 to I-0, overriding coal in final stages.